Continuum versus Discrete Flux Behaviour in Large Mesoscopic $Bi_2Sr_2CaCu_2O_{8+\delta}$ Disks

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Abstract

We have used scanning Hall probe and 'local' Hall magnetometry measurements to map flux profiles in superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ disks whose diameters span the crossover between the bulk and mesoscopic vortex regimes. The behaviour of large disks (≥ 20µm diameter) is well described by analytic models that assume a *continuous* distribution of flux in the sample. Small disks (≤ 10µm diameter), on the other hand, exhibit clear signatures of the underlying *discrete* vortex structure as well as competition between triangular 'Abrikosov' ordering and the formation of shell structures driven by interactions with circulating edge currents. At low fields we are able to directly observe the characteristic mesoscopic *compression* of vortex clusters which is linked to oscillations in the diameter of the vortex "dome" in increasing magnetic fields. At higher fields, where single vortex resolution is lost, we are still able to track configurational changes in the vortex patterns, since competing vortex orders impose unmistakable signatures on 'local' magnetisation curves. Our observations are in excellent agreement with molecular-dynamics numerical simulations which lead us to a natural definition of the lengthscale for the crossover between discrete and continuum behaviour in our system.

Keywords: vortex matter, mesoscopic type II superconductors, multiscale physics
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1. Introduction

Developing computational approaches that can span multiple lengthscales, *multiscale modelling,* is currently a major focus of theory and simulation. For example plasticity in metals is a phenomenon that bridges continuum elasticity and atomic-scale dislocation dynamics. Vortex matter is model system for studying multiscale physics; flux is discrete at the microscopic level and the vortex density and interaction strengths can be continuously tuned by varying the applied field. At long lengthscales continuum electrodynamics has been successfully used to describe type II superconductors with B, J_s etc. averaged over several vortex lattice spacings. At short lengthscales ($l \leq \lambda$, ξ) vortex-surface interactions in disks lead to the formation of concentric shell structures which can be well modelled in molecular dynamics simulations. An open question, however, remains; at what

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lengthscale should one cross over from a continuum description to a discrete description of vortex matter?

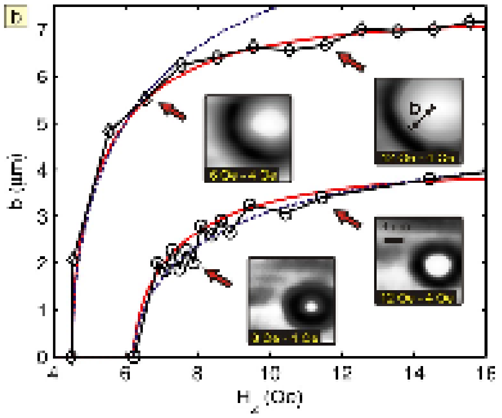

Fig. 1 (color on-line) Radius b of the vortex dome versus applied field, H_z, for 10 µm (○) and 20µm (◊) diameter disks. Insets show typical SHPM images used to extract experimental data.

2. Experiments and Simulations

Optical lithography and Ar-ion milling were used to pattern arrays of different diameter (20µm, 15µm, 10µm, 5µm) "disks" 300nm high on the surface of a single crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$ high temperature superconductor.

Scanning Hall probe microscopy (SHPM) was used to map flux profiles across the disks as a function of applied field, H_z, at 77K. The images inset in Fig. 1 show that for fields just above the penetration field, H_p, geometrical barriers lead to the formation of a central vortex "dome" [1,2] which expands with increasing applied field. Fig. 1 plots the radius, b, of the dome of penetrated flux as a function of the applied field for two disk sizes, 10 µm and 20 µm. The solid line is a fit to a continuum model for the vortex dome from reference [1], and we find quite good agreement with our data for reasonable fitting parameters.

While the fit to the continuum dome model is rather good for the 20 µm disks, it clearly fails to describe the oscillatory behaviour of $b(H_z)$ observed at low fields in 10 µm disks. SHPM images in these smaller disks at low fields reveal that oscillations are associated with the formation of vortex clusters containing a few (2-6) vortices. As the field is increased each cluster is compressed due to interaction with increasing Meissner currents at the disk edge up to the point where a new vortex penetrates and the size of the cluster increases again. A suitable expression for $b(H_z)$ in this *mesoscopic* limit, which accounts for the discrete composition of the dome, has been derived by Cabral *et al.* [3]. By considering the forces on vortices arranged in a regular polygon encircled by a ring of radius, b, Cabral *et al*. obtained $b(H_z)$ at which each vortex cluster becomes unstable with respect to the entrance of the next vortex. The best fits to this model are shown as dashed curves in Fig. 1. The qualitative fit to the data is excellent for the 10 µm disk but evidently fails for the 20 µm disk, strongly suggesting that the crossover from discrete to continuum behaviour occurs between these two disk sizes.

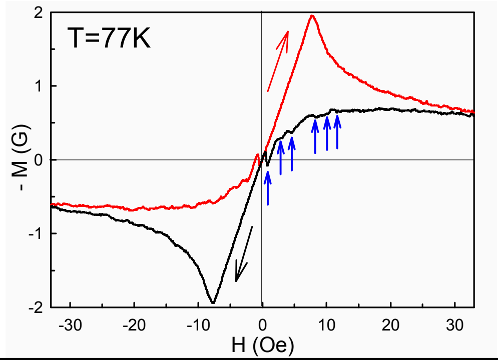

Fig. 2 (color on-line) Experimental "local" $M(H_z)$ curves, for increasing and decreasing fields. Vertical arrows highlight a few signatures of transitions between different stable vortex clusters.

Further evidence of mesoscopic vortex phenomena is found in the measured "local" magnetisation ($M_l = B_z - \mu_0 H_z$) captured with the SHPM Hall sensor parked at the centre of 10 µm disks (Fig. 2). Fully reproducible structures are observed upon ramping the applied field corresponding to transitions between vortex clusters of varying stability. Features observed in sweep-up and sweep-down curves can be linked and are remarkably well reproduced by molecular dynamics simulations with realistic sample parameters [4].

Finally we have used the competition between triangular "Abrikosov" ordering and deformation into vortex shells to construct an analytic criterion for the mesoscopic-macroscopic crossover. This predicts that it should occur at a disk diameter slightly larger than 10 µm, in fair agreement with our experimental observations [4].

Acknowledgments

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